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Correlation between X-ray and gamma-ray emission in TeV blazars

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Abstract. Blazars are well known as very active sources especially in the high energy range of the electromagnetic spectrum. The comparison between the X-ray and gamma-ray light curves in some blazars shows unexpected correlation. The correlation that cannot be easily explained by a standard model of the synchrotron self-Compton emission frequently used to explain the high energy emission in blazars. Therefore, it is very important to understand the nature of the correlation that may help to investigate many processes (e.g. particle acceleration) responsible for the blazars emission.
We review observational results that show the correlation, we explain why standard models of the emission are not able to explain the correlation and finally we propose a simple solution for the problem of the correlation.

Key words. Radiation mechanisms: non-thermal – Galaxies: active BL Lacertae objects

1. Introduction

Emission of some blazars is observed up to very high energy gamma rays where the photons energies are of about a few TeV. We call such sources TeV blazars. High energy spectra of such objects (multiplied by the frequency – νF_ν) show two characteristic peaks (e.g. Fossati et al. 1998). The maximum of the first peak appears in the X-ray range around a few teens of keV whereas the second peak maximum is observed in the TeV range. The variability time scales from days up to minutes indicate that the high energy emission must be generated in a compact region (< 1 pc) of a jet. This is probably a downstream region of a shock wave. Particles accelerated at the front of the shock are systematically filling this region (e.g. Kirk et al. 1998). The downstream region is also filled by the magnetic field therefore the particles spinning around tangled magnetic field lines are producing the synchrotron emission. This emission is observed as the first peak in the spectrum. The second peak is produced by the inverse-Compton (hereafter IC) scattering of the synchrotron radiation field by the same population of the particles that produces this synchrotron radiation. This is well known synchrotron self-Compton process (hereafter SSC). This also means that there must be some kind of correlation between the X-ray and the gamma-ray emission.

To describe the observed correlations it is necessary to assume that the X-ray and gamma-ray fluxes evolve in time as a power-law functions

$$F_{\rm X-ray} \propto t^s, \quad F_{\rm TeV} \propto t^c, \tag{1}$$

Send offprint requests to: K. Katarzyński in a short time scales, for example during rise or decay of a flare. Comparing the above equations we can write

$$F_{\mathrm{TeV}} \propto F^{x}_{\mathrm{X-ray}}, \qquad (2)$$

where $x = s/c$ is the slope of the correlation and the parameters s and c are different for rise and decay of a flare. This simple parametrisation can well describe the observed correlations obtained from the comparison of two different light curves.

2. Observations

The correlation between the X-ray and gamma-ray emission in TeV blazars was precisely observed only a few times so far.

The best results were obtained from the campaign of observations of Mrk 421 conducted in March 2001 by RXTE, HEGRA and Whipple instruments (Fossati et al. 2008). The comparison between the X-ray light curve in the energy range 0.2-10 keV and the gamma-ray observations above 0.4 TeV from the first night of this campaign (March 18/19) gives almost cubic correlation $x = 2.84 \pm 0.41$. This result is presented in Fig. 1. Note that the slope of the correlation seems to be similar for the rise and decay of the flare. The correlations obtained for the fourth and fifth night of this campaign give less than quadratic correlations $x = 1.56 \pm 0.25$ and $x = 1.67 \pm 0.16$ respectively. The results from the other nights of this seven days long campaign are rather ambiguous.

The observations of PKS 2155-304 conducted simultaneously by *Chandra* and H.E.S.S. instruments (Aharonian et al. 2009) shows almost cubic value of the correlation ($x \simeq 3$). What is important this correlation was obtained only for the decay phase of the flare.

The analysis of the archive observations of Mrk 501 from April 1997 (Catanese et al. 1997) demonstrates that the slope of the correlation may depends on the energy range of the observations. The comparison between the CGRO-OSSE light curve (50-150 keV) and the Whipple observations above 350 GeV resulted in $x = 1.71 \pm 0.50$ whereas the comparison between the same Whipple data and the X-ray light curve from RXTE-ASM (2-10 keV) give $x = 2.69 \pm 0.56$ (Katarzyński et al. 2005). The observations of Mrk 501 conducted in May 1997 by RXTE-PCU (2-10 keV) and the gamma-ray telescopes (Whipple & HEGRA) shows linear relation $x = 0.99 \pm 0.01$. However, the same instruments obtained almost quadratic correlation $x = 2.07 \pm 0.27$ from the observations of Mrk 501 in June 1998 (Gliozzi et al. 2006).

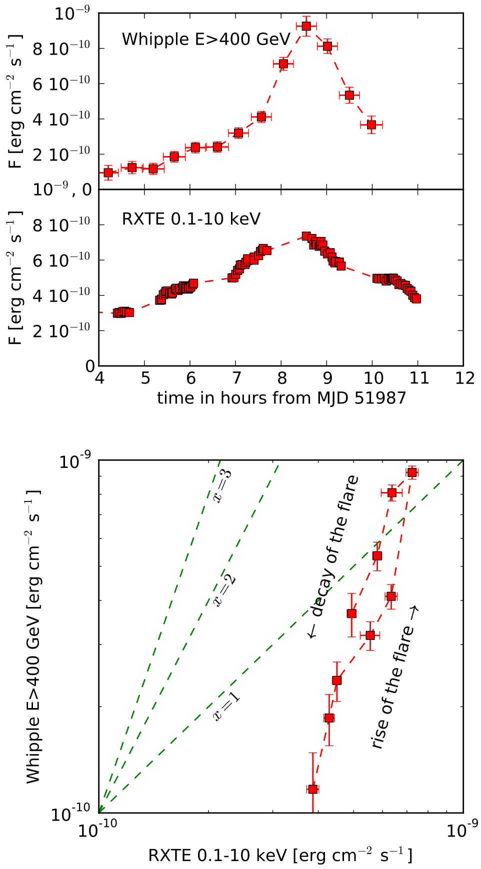

Fig. 1. Simultaneous X-ray and gamma-ray activity of Mrk 421 observed on March 18/19 2001 by RXTE and Whipple instruments (Fossati et al. 2008). The upper panels show the light curves whereas the lower panel shows the correlation and theoretical lines for comparison.

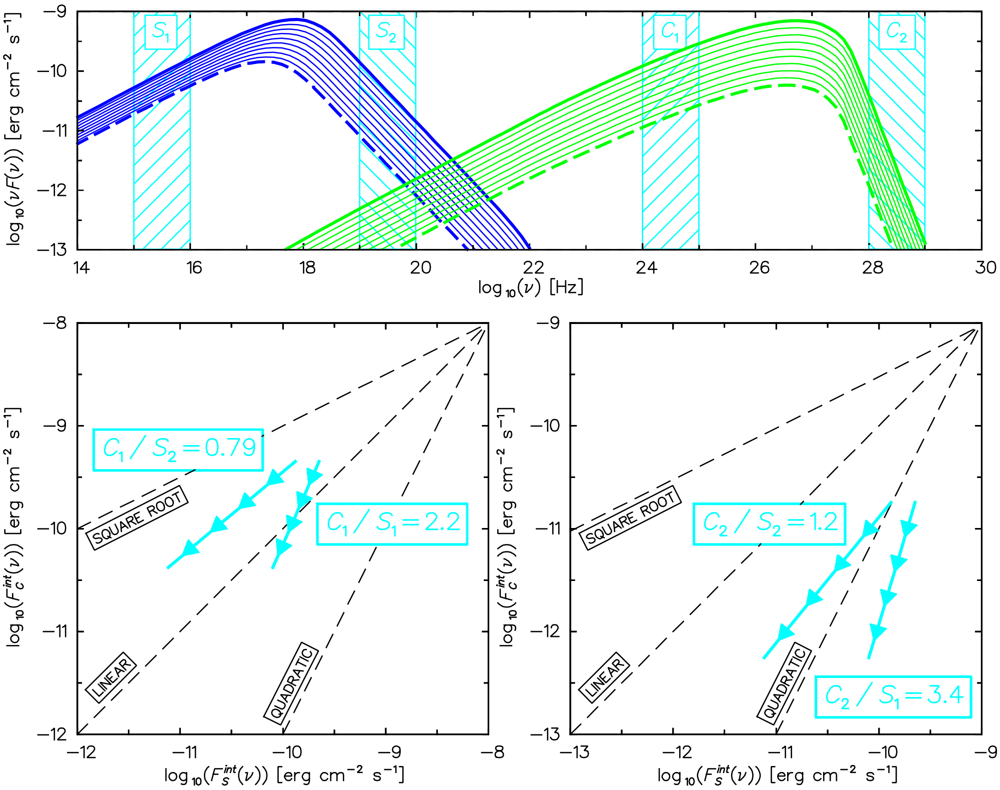

Fig. 2. An example of the spectrum evolution of adiabatically expanding homogeneous source (upper panel) and the obtained correlations (lower panels). The shaded vertical areas in the upper panel show energy ranges used for the calculation of the correlations presented in the lower panels.

Finally, in many cases the correlation was not observed or the obtained results were not enough precise to measure the slope (e.g. Albert et al. (2007), Horan et al. (2009), Bonnoli et al. (2009)). This not necessary means that the correlation is uncommon. Detection and measure of the correlation needs precise observations of relatively strong activity events simultaneously in at least two different energy ranges. This appears to be very problematic. Anyway, even if the correlation was observed only a few times so far, it should be possible to explain such evolution of the source emission. However, this appears to be problematic too.

It should be also mentioned that in at least two cases the gamma-ray flares were observed without counterpart X-ray events (e.g. Krawczynski et al. (2004), Blazejowski et al. (2005)). This may be an extreme case of the correlation with the infinite slope (x = inf).

3. Problem with single zone models

The simplest model that is frequently used to explain high energy emission of TeV blazars assumes homogeneous, spherical source filed uniformly by relativistic particles and magnetic field. Moreover, assumed particle energy distribution inside the source is usually a power-law or double (broken) power-law distribution. In such simple scenario it is possible to parametrise the evolution of the main physical parameters (source radius, particle density, magnetic field strength) and to estimate analytically the expected correlations (Katarzyński et al. 2005). An example of such estimation is presented in Fig. 2. The evolution of the synchrotron flux below the peak ($F_{\rm s} \propto t^{s_1}$) is different than above the peak ($F_{\rm s} \propto t^{s_2}$) . The same concerns the IC emission ($F_{\rm c} \propto t^{c_1}$ and $F_{\rm c} \propto t^{c_2}$ respectively). This gives in principle four different flux evolutions and four different correlations. However, the X-ray and gamma-ray emission in TeV blazars is usually observed above the synchrotron and the IC peak and only this relation is important ($x = c_2/s_2$). The detailed study of many different scenarios for the source evolution show that the correlation slope may change from a square root to quadratic value. However, for the most realistic cases, like for example the adiabatic expansion presented in Fig. 2, the correlation value should be linear or slightly more than linear.

The well known feature of the SSC emission is the quadratic increase/decrease of the IC flux with the increase/decrease of the particle density (K). This comes from the fact that the intensity of the synchrotron emission is proportional to the particle density $I_{\rm s} \propto K$ and the intensity of the IC emission is proportional to the particle density and the intensity of the synchrotron emission $I_{\rm c} \propto KI_{\rm s} \propto K^2$. Therefore, the change of the particle density could in principle explain the observed quadratic correlations. However, this requires simultaneous change of the density in the whole volume of the source. Moreover, the other physical parameters must remain constant during this change. This makes this scenario rather unrealistic.

Finally, in some cases the observed slope of the correlation was almost cubic and this lies beyond the capabilities of the single zone SSC modelling. To summarise, the single zone model can explain linear or slightly more than linear correlation ($x \simeq 1.2$). The quadratic relation is already problematic for such model and the cubic slope seems to be impossible to explain. For more details about the capabilities of such models see Katarzyński et al. (2005).

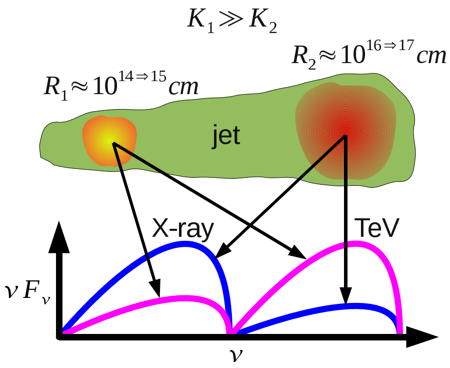

Fig. 3. The sketch that explains the idea of simultaneous emission of two sources.

4. At least two sources?

The correlation problem can be solved when we assume simultaneous emission of at least two sources. This idea is illustrated in Fig. 3. The first source is relatively compact (radius $R \sim 10^{14\rightarrow15}$ cm) and dense (K_1). The small volume causes relatively low level of the synchrotron emission but the IC emission of this source is very efficient due to the high density. The second source is two order of magnitude bigger ($R \sim 10^{16\rightarrow17}$ cm) than the first one but the particle density inside this object is relatively small ($K_2 \ll K_1$). The big volume gives a lot of the synchrotron radiation but the small density gives almost negligible gamma-ray emission. Moreover, the variability time scale of the second source must be much longer than the variability of the first object. In some sense the second source provides almost constant X-ray emission background. Such background, dominant in the X-ray range, is reducing the amplitude of the of the first source X-ray variability, whereas the amplitude of the gamma-ray activity remains unchanged. Calculating the correlation we in fact compare amplitudes of a flare in the two different energy ranges. If the amplitude of the gamma-ray activity increase by the same factor as the amplitude of the X-ray flare then the correlation is linear. If the amplitude of the gamma-ray activity is increasing two times faster than the amplitude of the X-ray emission then the correlation is quadratic. Therefore, the X-ray background that reduces the amplitude of the X-ray activity, increases the correlation slope.

The simple combination of the two sources emission can explain any slope of the correlation even the cases where the correlation is infinite. It is also worth to mention that the same approach was used to explain another puzzling behaviour of TeV blazars - the rapid variability (Katarzyński et al. 2008).

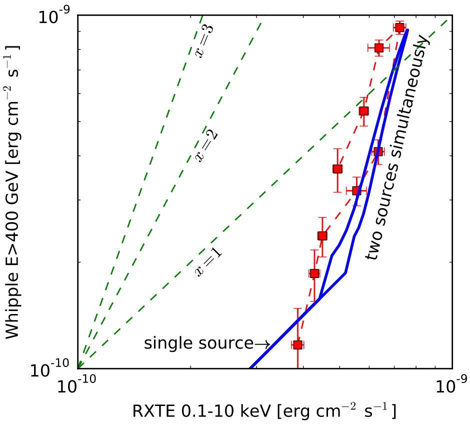

Fig. 4. The modelling of the correlation presented in Fig. 1 with the assumption that the activity is generated by the beaming effect.

5. Rise and decay - the same slope?

Most of the blazar emission models explain the activity by a change of the particle energy distribution inside a source. The high energy emission requires relativistic particles ($E = \gamma m_e c^2$ where the Lorentz factor is $\gamma \sim 10^5 \rightarrow 10^7$). The particles can reach such extremely high energies at the front of a shock wave that systematically accelerates the particles. As long as the shock is working the source emission level can increase. However, when the efficiency of the acceleration decreases the radiative cooling becomes dominant and the emission decreases too. This is the simplest and the most popular explanation for the high energy activity of blazars. What is important, two completely different physical processes control the rise (acceleration) and the decay (radiative cooling) of a flare. This basically means that the correlation slope in the rising phase of a flare can be different than the correlation in the decay. Indeed, the simulations show that the correlation is different in this two phases of the activity (Katarzyński & Walczewska 2010). On the other hand some observations (e.g. Fig. 1) are suggesting that the correlation slope is similar for the raise and decay of a flare.

The simple effect that can provide the same correlation for the rise and decay is the beaming effect. Emission of relativistically moving sources ($v = \beta c$) is confined by a beam with the half opening angle $\phi \simeq 1/\Gamma$ where Γ is the source bulk motion Lorentz factor $\Gamma = 1/\sqrt{1-\beta^2}$. Therefore, the observed flux is strongly amplified $F_{\rm obs}(\nu) = \delta^3 F_{\rm src}(\nu)$ where $\delta = 1/(\Gamma(1-\beta\cos\theta))$ is the Doppler factor and θ is the angle between the source velocity and the direction to the observer. If the source travels along a curved trajectory then the change of θ will modify the level of the emission. Such generated activity will be frequency independent and the X-ray and gamma-ray flux will evolve in the same way. This gives linear correlation for the rise and decay of a flare. Thus again it is necessary to assume simultaneous emission of at least two independent sources to obtain quadratic or cubic correlation slope as it was demonstrated in the previous section.

The Fig. 4 shows an example of the modelling where the activity was simulated by a simple change of the Doppler factor value of two independent sources. At the beginning of the activity only the big source is radiating therefore the correlation is linear. The emission of the the second, small source changes the correlation slope to almost cubic and the slope is almost identical for the rise and decay of the activity. For more details about this modelling see Katarzyński & Walczewska (2010).

6. Summary

The correlation was observed only a few times so far. However, this was enough to show that the single zone SSC modelling is not able to explain the steep slopes of the correlation. The simple solution for this problem is simultaneous emission of two different sources that can explain any slope.

It seems that in some cases the correlation has the same slope in the rise and decay of the activity. This is another problem for the SSC emission model because it gives different slopes. The simple solution is to assume that the activity is generated mostly by the change of the Doppler factor. Such simple approach can well explain the correlation observed on March 18/19 in Mrk 421.

The existing models with simple modifications described in this paper can well explain the observed correlations. However, the correlation needs further intense investigation as it may provide significant constrains for the blazar emission mechanisms.

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